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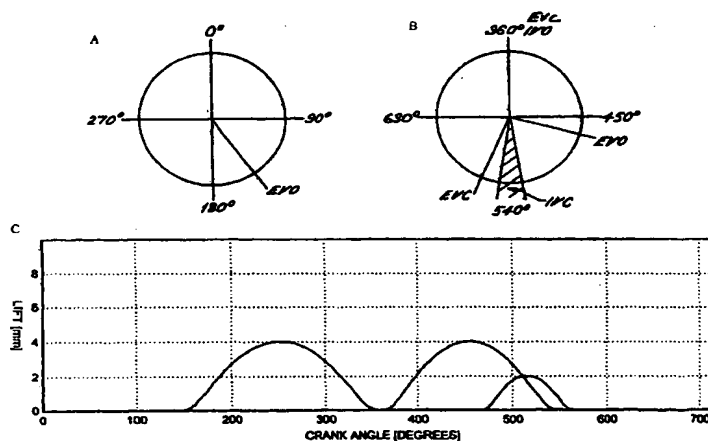
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(54) Title: **AN AUTO-IGNITED HOMOGENOUS CHARGE FOUR STROKE ENGINE**



(57) Abstract: The present invention provides a method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process. Flow of fuel/air charge into and flow of combusted gases from at least one combustion chamber (12) is regulated by valve means (15, 16) in order to ensure that the fuel/air charge is mixed with combusted gases so as to generate conditions in the combustion chamber (12) suitable for operation of an auto-ignition process. The valve means (15, 16) used comprises an inlet valve (15) controlling flow of fuel/air mixture into the combustion chamber from an inlet passage (13). The valve means (15, 16) used comprises an exhaust valve (16) controlling exhaust of combusted gases from the combustion chamber (12) to an exhaust passage (14). The exhaust valve (16) is opened for a first period during a four-stroke cycle to allow combusted gases to be expelled from the combustion chamber (12). The exhaust valve (16) is opened for two separate periods during the same four stroke cycle, with the exhaust valve (16) being opened for a second period to allow combusted gases previously exhausted from the combustion chamber (12) to be drawn back into the combustion chamber (12).

WO 01/46571 A1

- 1 -

**AN AUTO-IGNITED HOMOGENOUS CHARGE FOUR STROKE ENGINE**

The present invention relates to a four-stroke internal combustion engine.

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Increasingly stringent fuel economy and emissions targets are being imposed by government legislation. These and consumer pressures continually force the automotive industry to investigate new ways of improving the combustion process of the internal combustion engine.

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Once such approach is the auto-ignition (AI) process. In this process a mixture of combusted gases, air and fuel is created which ignites without the need for a spark during compression. The process is sometimes called self-ignition. It is a controlled process and thus differs from the undesirable pre-ignition which has been known in some spark-ignition engines. It differs from compression ignition in diesel engines because in a diesel engine the diesel fuel ignites immediately on injection into a pre-compressed high temperature charge of air, whereas in the auto-ignition process the fuel and air and combusted gases are mixed together prior to combustion. Use of the auto-ignition process in two-stroke engines is well known. The present invention relates to the application of this process to a four-stroke internal combustion engine.

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In US 6082342 there is described a four-stroke internal combustion engine which provides for auto-ignition by controlling the motion of the inlet and exhaust valves of a combustion chamber to ensure that a fuel/air charge is mixed with combusted gases to

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- 2 -

generate conditions suitable for auto-ignition. US 6082342 describes an engine with a mechanically cam-actuated exhaust valve which is closed later in the four-stroke cycle than usual in a normal four-stroke engine to allow for the exhaust valve to be simultaneously open with an intake valve and to allow previously expelled combusted gases to be drawn back into the combustion chamber. Additionally, there is described an engine in which an exhaust valve is closed early in the exhaust stroke to trap combusted gases for subsequent mixing with an intake of fuel and air mixture. In both engines the exhaust valve is opened only once in each four stroke cycle.

15           The present invention provides a method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process and in which flow of fuel/air charge into and flow of combusted gases from at least one combustion chamber is regulated by valve means in order to ensure that the fuel/air charge is mixed with the combusted gases so as to generate conditions in the combustion chamber suitable for operation of an auto-ignition process, wherein the valve means used comprises an inlet valve means controlling flow of fuel/air mixture into the combustion chamber from an inlet passage and exhaust valve means controlling exhaust of combusted gases from the combustion chamber to an exhaust passage and wherein the exhaust valve means is opened during a four-stroke cycle for a first period to allow combusted gases to be expelled from the combustion chamber, characterised in that:

          during the said four stroke cycle the exhaust valve means is opened for two separate periods, with the exhaust valve means being opened for a second

- 3 -

period to allow combusted gases previously exhausted from the combustion chamber to be drawn back into the combustion chamber.

5           The double opening of the exhaust valve means in each four stroke cycle reliably creates the conditions necessary for auto-ignition in the combustion chamber.

10           Preferred embodiments of the present invention will be described with reference to the following figures:

          Figure 1 is a schematic illustration of a first embodiment of single cylinder four-stroke engine according to the present invention;

15           Figures 2a and 2b are valve timing diagrams for the exhaust and inlet valves of a single cylinder of a single cylinder four-stroke internal combustion engine operating according to a conventional method of operation;

20           Figures 3a, 3b and 3c are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to the method of the present invention, in a first regime;

25           Figure 4 is a schematic illustration of a second embodiment of single cylinder four-stroke engine according to the present invention;

          Figure 5 is a schematic illustration of a third embodiment of single cylinder four-stroke engine according to the present invention;

30           Figures 6a, 6b and 6c are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine having two exhaust valves operating according to a variation of

- 4 -

the first regime; and

Figure 7 is a schematic illustration of a fourth embodiment of single cylinder four-stroke engine according to the present invention.

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For simplicity, the detailed description following will address the method of the present invention in its application to a single cylinder four-stroke internal combustion engine, although it should be appreciated that the present invention is equally applicable to a multicylinder four-stroke internal combustion engine.

A schematic representation of a first embodiment of a single-cylinder four stroke internal combustion engine is given in Figure 1. In the Figure a piston 10 is movable in a cylinder 11 and defines with the cylinder 11 a variable volume combustion chamber 12.

An intake passage 13 supplies a mixture of fuel and air into the combustion chamber 12. The flow of the fuel-air charge into the combustion chamber 12 is controlled by an intake valve 15.

Combusted gases can flow from the combustion chamber 12 via an exhaust passage 14 and flow of combusted gases through the exhaust passage 14 is controlled by the exhaust valve 16.

The inlet valve 15 and the exhaust valve 16 are hydraulically actuated. It can be seen in the Figure

- 5 -

that the stem 17 of the inlet valve 15 has provided thereon a piston 18 which is movable in a cylinder 19. Similarly, the stem 20 of the exhaust valve 16 has a piston 21 provided thereon which is movable in a cylinder 22.

Flow of hydraulic fluid to the cylinder 19 is controlled by a servo-valve 23. The servo-valve 23 is electrically controlled. The servo-valve 23 is controlled by control signals generated by the electronic controller 24. The servo-valve 23 can control hydraulic fluid to flow into an upper chamber 25 of an arrangement of the piston 18 and the cylinder 19 whilst controlling flow of hydraulic fluid out of a lower chamber 26. The servo-valve 23 can also control flow of hydraulic fluid to and from the cylinder 19 such that hydraulic fluid is delivered to the bottom chamber 26 whilst hydraulic fluid is expelled from the upper chamber 25. The fluid supplied to and expelled from the cylinder 19 is metered, so as to control exactly the position and/or velocity of the inlet valve 15.

In a similar fashion, a servo-valve 27 is provided to control flow of hydraulic fluid to and from the cylinder 22. The servo-valve 27 is controlled electrically by the electronic controller 24. The servo-valve 27 can operate to supply hydraulic fluid under pressure to an upper chamber 28 of a cylinder 22 whilst allowing hydraulic fluid to be expelled from the lower chamber 29 of the cylinder 22. Conversely, the servo-valve 27 can allow pressurised hydraulic fluid to be supplied to the lower chamber 29 whilst allowing hydraulic fluid to be expelled from the upper chamber 28. The servo-valve 27 meters the

- 6 -

flow of hydraulic fluid to and from the cylinder 22 in order to control the position and/or the velocity of the exhaust valve 16.

5 Both of the servo-valves 23 and 27 are connected to a pump 30 and a sump 31. Hydraulic fluid under pressure is supplied by the pump 30 and when hydraulic fluid is expelled from either or both of the cylinders 19 and 22 it is expelled to the sump 31. The pump 30  
10 will in practice draw fluid from the sump 31 to pressurise the fluid and then supply the pressurised fluid to the servo-valves 23 and 27.

The electronic controller 24 will control the  
15 movement of the inlet valve 15 and exhaust valve 16 having regard to the position of the inlet and exhaust valves 15 and 16 as measured by two position transducers 32 and 33. The controller 24 will also have regard to the position of the engine, which will  
20 be measured by a rotation sensor 34 which is connected to a crank shaft 35 of the internal combustion engine, the crank shaft 35 being connected by a connecting rod 36 to the piston 10 reciprocable in the cylinder 11.

25 The engine of the present invention has an hydraulically controlled valve train with an electronic controller 24 which is programmable and hydraulically controls the opening and closing of both the inlet 15 and exhaust 16 valves. This enables  
30 control of the motion of the inlet 15 and exhaust 16 valves and in particular the time (in terms of the engine cycle) when the inlet 15 and exhaust 16 valves open and the duration of time for which they are open.

35 Conventional four-stroke internal combustion

- 7 -

engines have cam shafts which drive the inlet and exhaust valves. The cam shafts have cam profiles which are designed to maximum the gas flow through the engine. Such engines rely on a spark plug to  
5 ignite the mixture. They also rely on an intake throttle to reduce gas flow and therefore control the power output of the engine.

In an engine according to the present invention  
10 the movement of the inlet 15 and exhaust 16 valves will be used for total gas flow management, controlling both the amount of air flowing into and out of the combustion chamber 12 during each stroke of the engine and also controlling the internal mixing  
15 process between the different gas species inside the combustion chamber 12 and also to an extent inside the inlet passage 13 and exhaust passage 14. The valve motion in the internal combustion engine according to the present invention will be very different from the  
20 motion of inlet and exhaust valves controlled by a conventional mechanical cam shaft. The valve motion will comprise different duration valve opening periods, different height lifts and a different number of lifts in each stroke. This will allow the engine  
25 valves 15 and 16 to control gas flow, engine load/power and also the timing of combustion within the engine. There will therefore be a reduced need for a throttle system and a reduced need for a spark plug. It may be that a spark plug is used only on  
30 start up of the engine or at low temperatures-or in high load/high speed operating conditions.

The auto-ignition process is already well-known in two-stroke engines. It provides improved fuel  
35 consumption, a lower engine emission (principally



- 8 -

lower lower hydrocarbons and carbon monoxide) and improved combustion stability. The two-stroke engine is an ideal engine for auto-ignition because auto-ignition relies upon the retention of some exhaust gas in the combustion chamber and a two-stroke engine can easily facilitate this, because the process of scavenging exhaust gases can be controlled to leave the required residual amount of exhaust gas in the mixture of fuel and air ready for combustion. Auto-ignition can provide reproducible combustion time after time.

Control of the motion of the inlet valve 15 and exhaust valve 16 in accordance with the present invention is illustrated with reference to Figures 3a, 3b and 3c as well as 6a, 6b and 6c, with Figures 2a and 2b giving an operating regime of normal camshaft operated valves for comparison.

Figures 2a and 2b show typical valve motion in a standard four-stroke internal combustion engine. The zero degree position is the beginning of the expansion stroke of the engine. Figure 2a shows that the exhaust valve opens in the expansion stroke roughly 30 degrees before bottom dead centre and Figure 2b shows that the exhaust valve remains open throughout the exhaust stroke to close at the beginning of the induction stroke at roughly 10 degrees after top dead centre. Figure 2a also shows that the inlet valve begins to open at the end of the exhaust stroke about 10 degrees before top dead centre, remains open throughout the induction stroke and Figure 2b shows that the inlet valve closes in the beginning of the compression stroke at about 45 degrees after bottom dead centre. A fuel/air charge is introduced into the combustion

- 9 -

chamber via the open inlet valve. Then the fuel/air charge is ignited by sparks compressed and then as the combustion occurs and the gases expand in the power stroke.

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Figures 3a, 3b and 3c illustrate an operating regime according to the present invention. In this operating regime the exhaust valve 16 is opened twice during each 360 degree rotation of the crankshaft 35.

10 The exhaust valve 16 is opened for the first time during an engine cycle at roughly 30 degrees before bottom dead centre at the end of the expansion stroke (see Figure 3a). The exhaust valve 16 is then closed for the first time at the end of the exhaust stroke

15 and the inlet valve 15 is simultaneously opened (see Figure 3b). The inlet valve 15 remains open at least for the majority of the induction stroke and closes during a range of 10 degrees before to 10 degrees after the bottom dead centre point of the piston 10 at

20 the end of the induction stroke (see Figure 3b). The exhaust valve 16 is opened for the second time during the same engine cycle at roughly 80 degrees before the piston 10 reaches bottom dead centre at the end of the induction stroke (see Figure 5b). The exhaust valve

25 16 is closed for the second time during the single engine cycle at roughly 20 degrees of crankshaft rotation past the bottom dead centre portion of the piston 10 at the end of the induction stroke (see Figure 3b).

30

In the operating regime of the present invention the exhaust valve 16 is opened twice during a single engine cycle. During the first period of opening combusted gases are expelled for the combustion

35 chamber to the exhaust passage 14. During the second

- 10 -

period of opening previously exhausted combusted gases are drawn back into the combustion chamber from the exhaust passage 14 at the same time as a fuel-air charge is drawn into the combustion chamber 12 through the inlet passage 13. Thus mixing of combusted gases and fresh fuel-air charge is achieved and promotes the correct conditions for auto-ignition. Auto-ignition of the mixture of combusted gases, fuel and air occurs after compression of the mixture during the compression stroke. The combustion of the mixture then causes the gases to expand in the power stroke. The four stroke cycle then starts again. It should be noted that the maximum lift of the exhaust valve 16 is less when opened for the second time in each engine cycle.

With an engine operating according to the operating regime of the present invention, it is preferred that the flow of exhaust gases through the passage 14 is to some degree throttled or restricted to establish a back pressure behind the exhaust valve 16 which facilitates flow of exhausted gases back into the combustion chamber 12 when the exhaust valve 16 is opened for the second period in the engine cycle.

Figure 4 shows a restrictor 40 present in the exhaust passage 14 to restrict flow of exhaust gases. The restrictor 40 provides an orifice 41 of a cross-section smaller than the cross-section of the exhaust passage 14.

Figure 5 shows a variable throttle 50 which can throttle the flow of exhaust gases to a variable degree. The throttle is a butterfly valve mounted on a spindle and connected to an electric motor 51. The electric motor 51 is controlled by the electronic

- 11 -

controller 24. The controller 24 receives a signal from a pressure sensor 52 present in the exhaust passage 14 and controls the electric motor to control the position of the valve 50 to throttle the combusted gases to achieve a desired back pressure behind the exhaust valve 16 when the exhaust valve 16 opens for a second time in an engine cycle. The use of a throttle 50 to provide variable throttling is preferable to provide for different operating conditions with varying engine speeds and loads.

Figures 6a, 6b and 6c show a variation of the operating regime suitable for an engine as shown in Figure 12 which has two exhaust valves 16 and 116 per cylinder as shown in Figure 7 each controlled by a separate actuator (21,22; 121,122) controlled each by a servo-valve (27; 127) controlled in turn by the electronic controller 24. Both of the exhaust valves 16 and 116 will lead to a common exhaust passage 14. A first exhaust valve 16 is opened roughly 45 degrees before bottom dead centre at the end of the power stroke. The exhaust valve 16 is then kept open until the end of the exhaust stroke when it is closed and an inlet valve 15 (or a pair of inlet valves) is opened simultaneously. The inlet valve 15 (or valves) is kept open until roughly 10 degrees after the end of the induction stroke. The second exhaust valve 116 is opened during the induction stroke at roughly 80 degrees of crankshaft rotation before the bottom dead centre position of the piston 10 at the end of the induction stroke and closed roughly 30 degrees after the said bottom dead centre position.

The maximum lift of the first exhaust valve 16 is higher than the maximum lift of the second exhaust

- 12 -

valve 116 and the maximum lift of the second exhaust valve 16 is comparable to the maximum lift of the inlet valve 15(or valves).

- 5           The variation in the operating regime avoids the need for any single valve to be opened twice during a single engine cycle.

10           Restriction or throttling of the exhausted gases flowing through the exhaust passage by a throttle such as variable throttle 50 will be as advantageous in the Figure 7 engine as in the Figures 4 and 5 engine.

15           If there are two inlet valves per cylinder, and if the motion of each inlet valve is separately controlled then the inlet valves could be controlled to have differing motions and thereby create swirl of the gases in the combustion chamber to promote mixing and to promote the correct conditions for auto-  
20           ignition.

          As mentioned above, whilst the simple engine shown above does not have a spark plug, it may prove necessary to use a spark plug to complement the auto-  
25           ignition process, particularly in start-up conditions. Also, it may also prove preferable to rely on auto-ignition only in part-load/low speed operating conditions and to use spark ignition during high load/high speed operating conditions.

30           Whilst the inlet valve 15 and exhaust valve 16 in the above embodiments are both hydraulically actuated, they could be valves actuated purely electrically or by electromagnetic forces.

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- 13 -

With the engine of the present invention it will not be necessary to pre-heat the fuel/air charge prior to admission into the combustion chamber in order to achieve auto-ignition.

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- 14 -

## CLAIMS

1. A method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process and in which flow of fuel/air charge into and flow of combusted gases from at least one combustion chamber is regulated by valve means in order to ensure that the fuel/air charge is mixed with the combusted gases so as to generate conditions in the combustion chamber suitable for operation of an auto-ignition process, wherein:

the valve means used comprises an inlet valve means controlling flow of fuel/air mixture into the combustion chamber from an inlet passage and exhaust valve means controlling exhaust of combusted gases from the combustion chamber to an exhaust passage; and wherein:

the exhaust valve means is opened during a four-stroke cycle for a first period to allow combusted gases to be expelled from the combustion chamber, characterised in that:

during the said four stroke cycle the exhaust valve means is opened for two separate periods, with the exhaust valve means being opened for a second period to allow combusted gases previously exhausted from the combustion chamber to be drawn back into the combustion chamber.

2. A method as claimed in claim 1 wherein the flow of combusted gases through the exhaust passage is restricted by use of a restrictor in the exhaust passage.

3. A method as claimed in claim 1 or claim 2 wherein the flow of combusted gases through the exhaust passage is throttled by use of a throttle in the

- 15 -

exhaust passage and wherein the method comprises controlling the throttle to provide varying degrees of throttling of the flow of combusted gases through the exhaust passage.

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4. A method as claimed in any one of claims 1 to 3 wherein the inlet valve means and the exhaust valve means are simultaneously open for at least part of the second period of opening of the exhaust valve means.

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5. A method as claimed in any one of claims 1 to 4 wherein the exhaust valve means used comprises at least two independently movable exhaust valves, a first exhaust valve which is opened during the first period of opening of the exhaust valve means and which is closed during the second period of opening of the exhaust valve means and a second exhaust valve which is closed during the first period of opening of the exhaust valve means and which is open during the second period of opening of the exhaust valve means.

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6. A method as claimed in any one of the preceding claims wherein the combustion chamber is a variable volume chamber defined in a cylinder by a piston reciprocating in the cylinder and wherein the opening and closing of the valve means is controlled by an electronic processor which operates according to a programme of instructions and which receives an input signal indicative of the position of the piston reciprocating in the cylinder.

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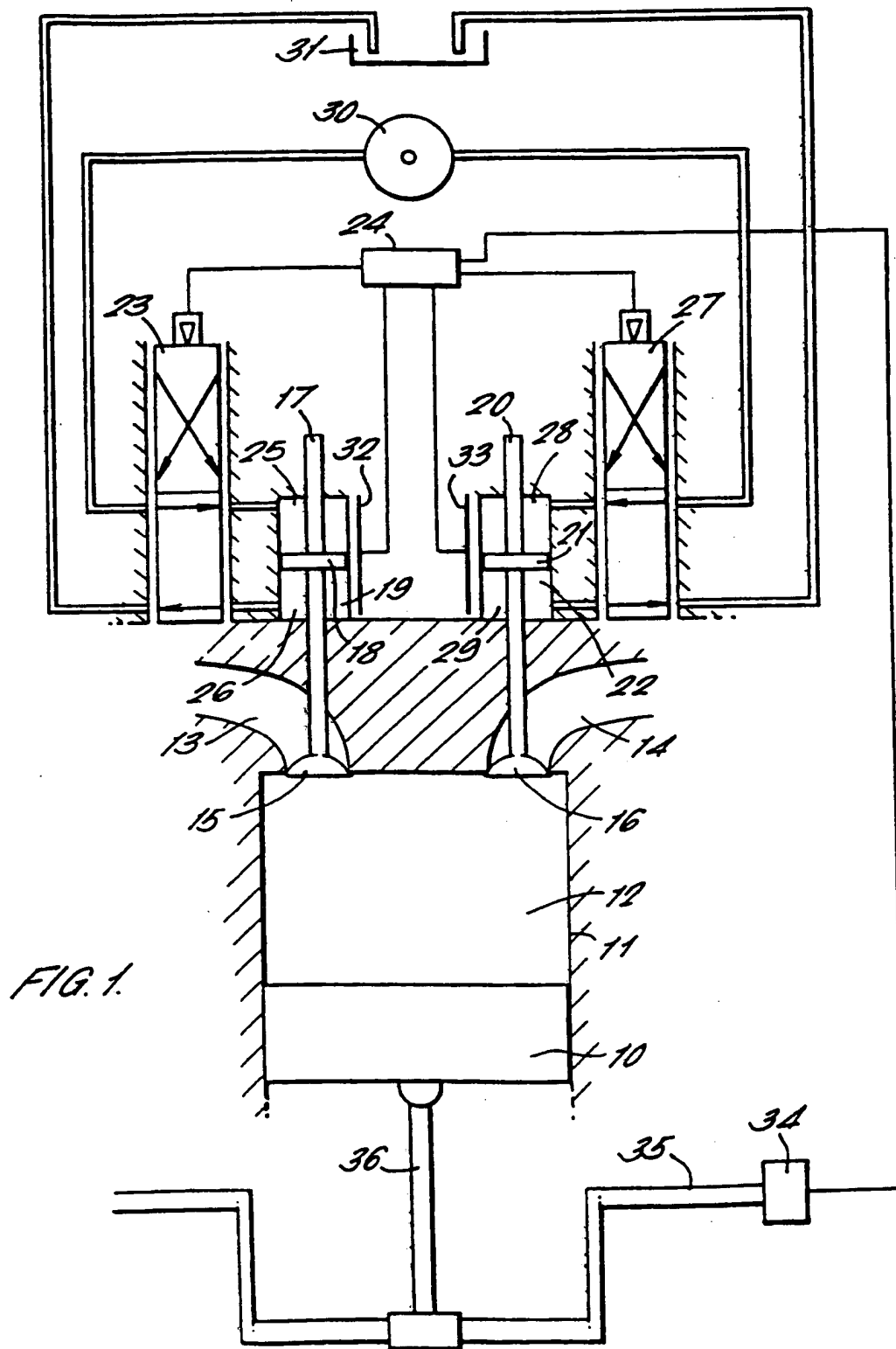
7. A method as claimed in claim 6 wherein the valve means comprises hydraulically actuated valves controlled by the electronic processor.

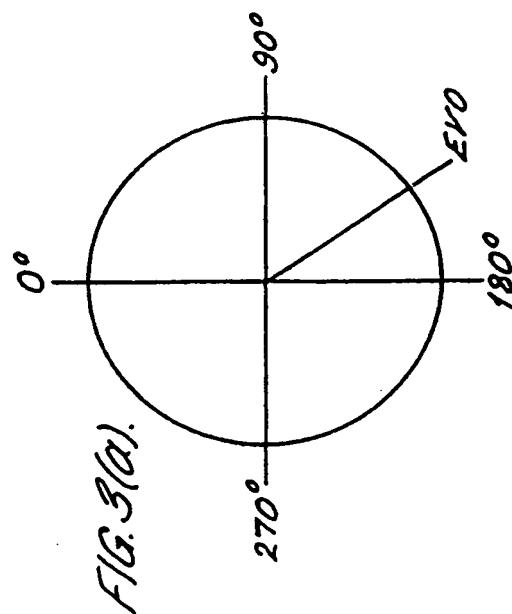
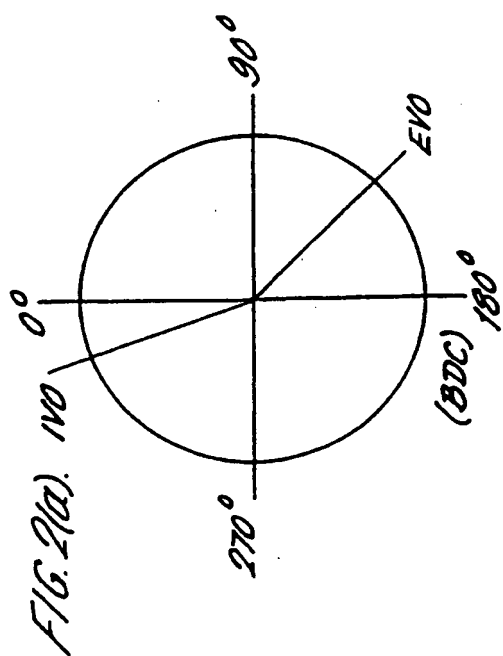
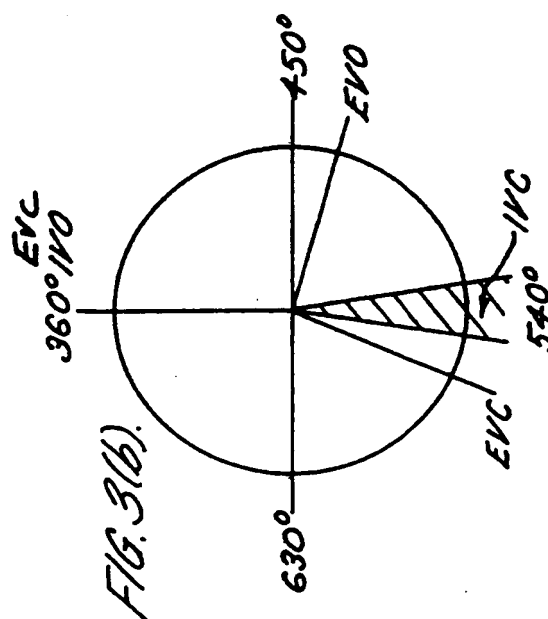
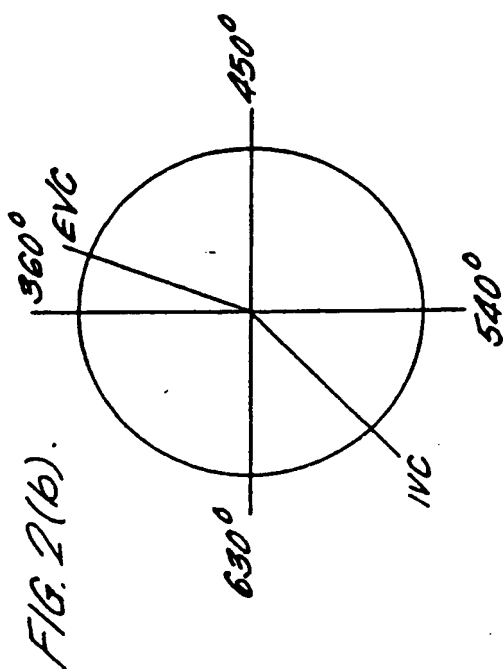
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- 16 -

8. A method as claimed in claim 7 wherein the hydraulically actuated valves are poppet valves.
9. A method as claimed in any one of the preceding claims comprising the step of pressuring the fuel/air mixture by supercharging or turbocharging prior to admitting the fuel/air mixture into the combustion chamber.
10. A four-stroke internal combustion engine operated according to a method as claimed in any one of the preceding claims.





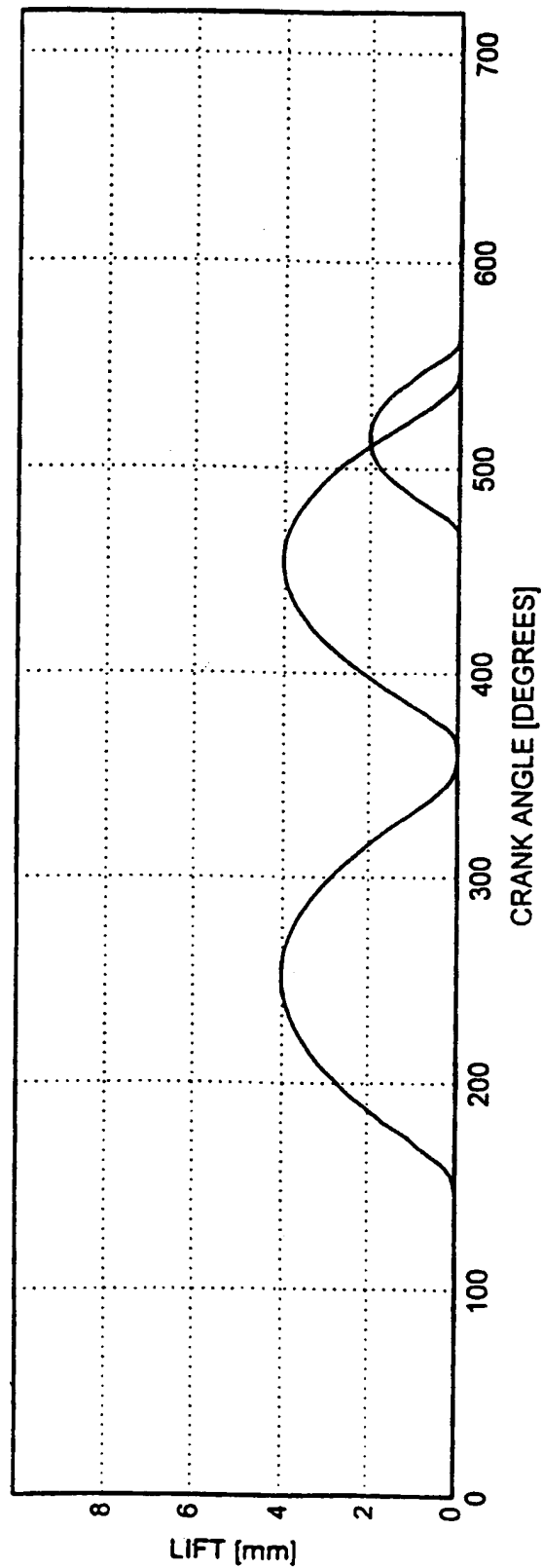
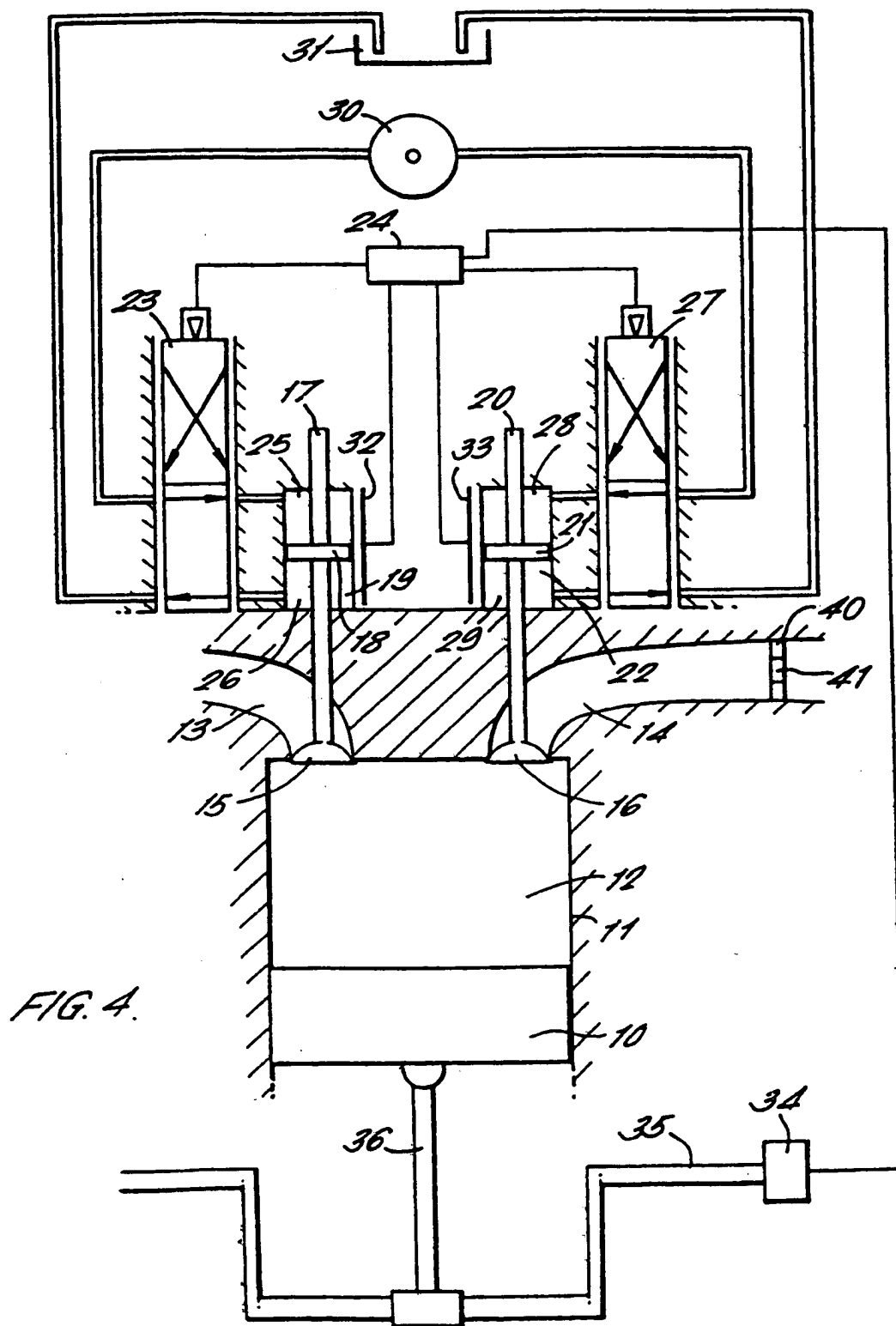
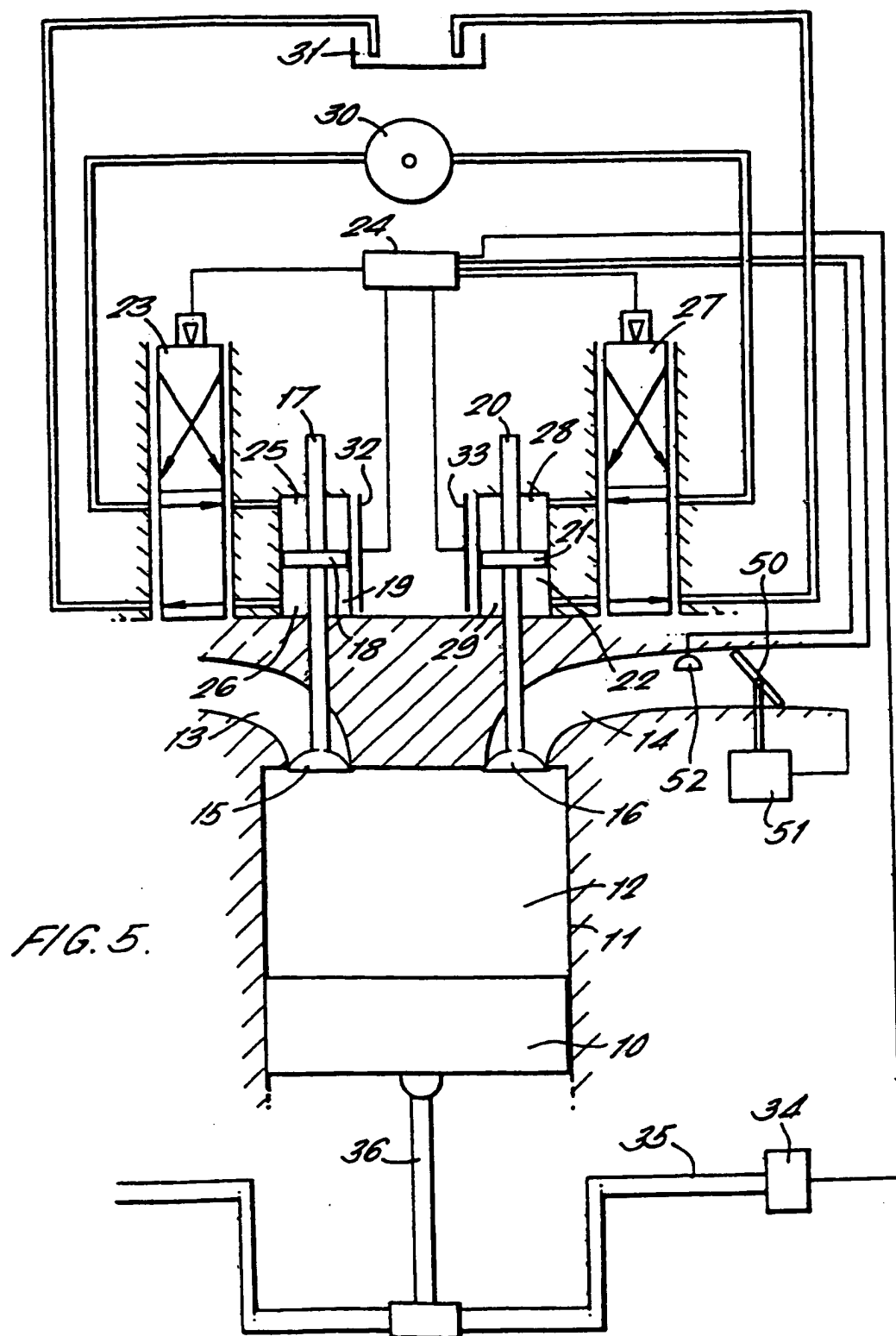
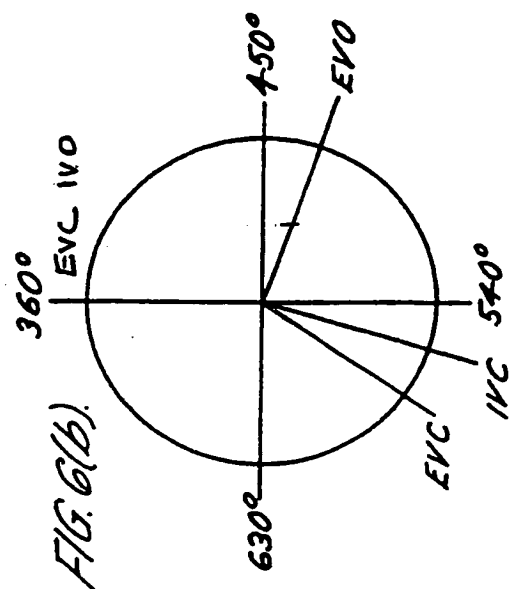


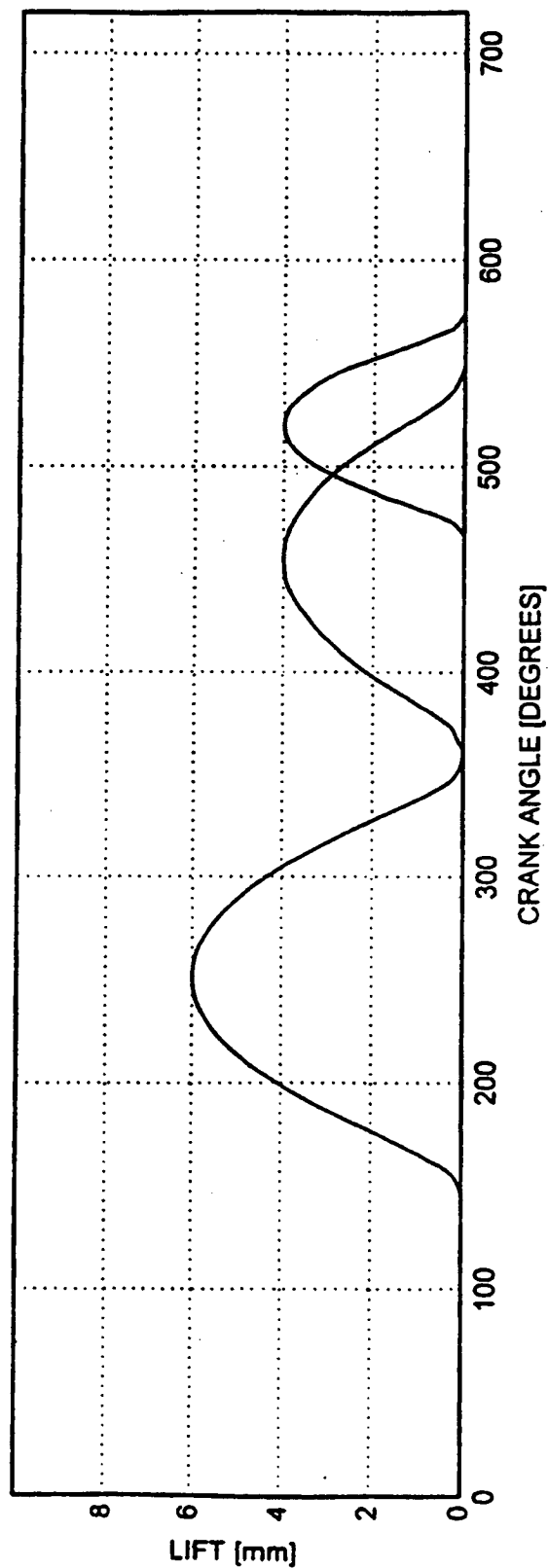
FIG. 3(c).





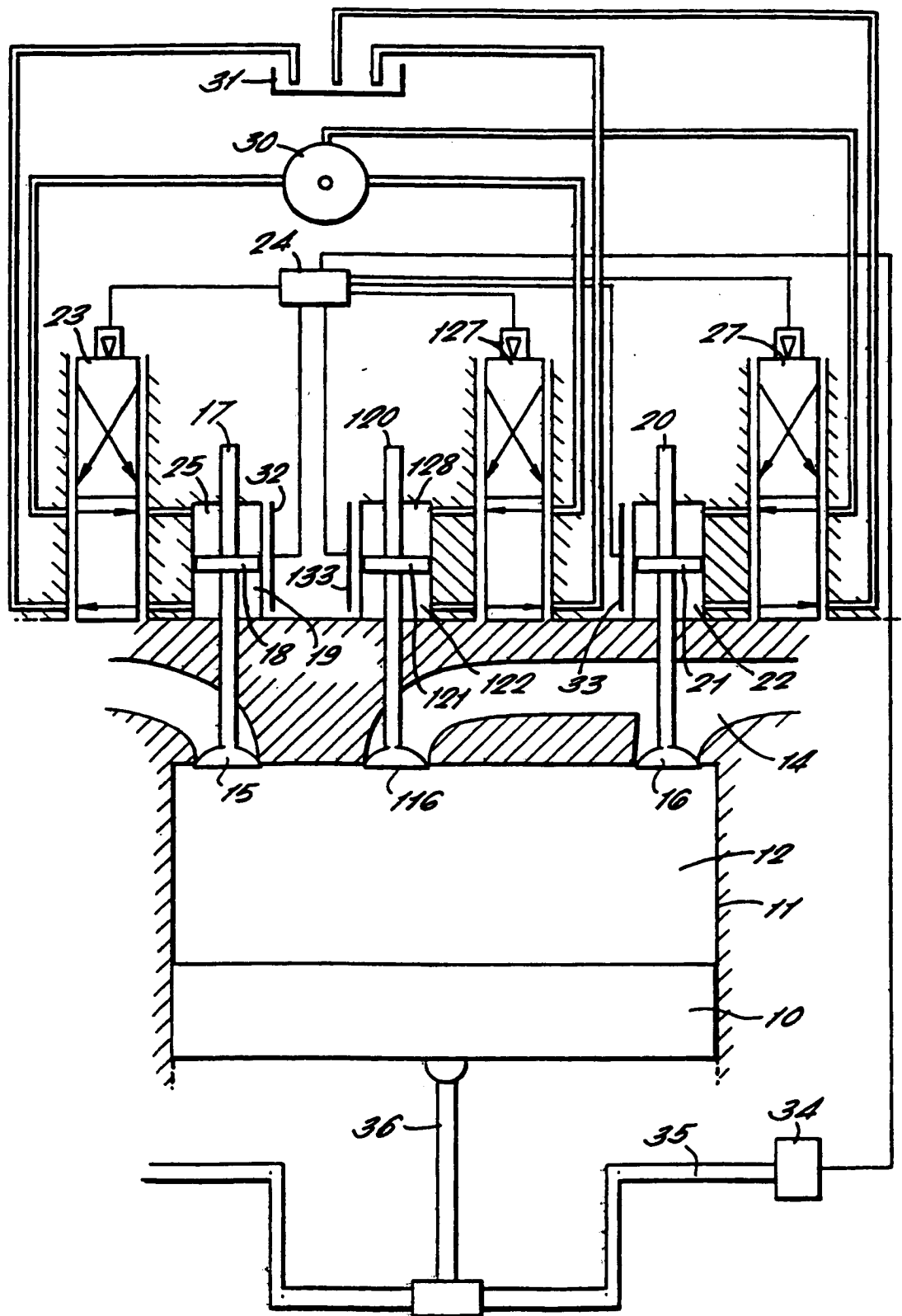


*FIG. 6(b)*



*FIG. 6(c)*

FIG. 7.





# INTERNATIONAL SEARCH REPORT

International Application No <b>PCT/GB 00/04974</b>		
<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC 7 F02B1/12 F02B11/00 F02D13/02 F01L9/02 F02M25/07		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b> Minimum documentation searched (classification system followed by classification symbols) IPC 7 F02D F02M F02B F01L		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, WPI Data, PAJ, COMPENDEX, INSPEC		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 99 42718 A (CUMMINS ENGINE CO INC) 26 August 1999 (1999-08-26)	1-6,9,10
A	the whole document	7,8
Y	US 5 809 964 A (MEISTRICK ZDENEK; PITZI VINCENT) 22 September 1998 (1998-09-22)	1-6,9,10
A	abstract; figures 1,5-9 column 6, line 40 -column 7, line 59 column 11, line 9 -column 13, line 20 column 14, line 45 -column 15, line 54 column 16, line 34 - line 58 column 22, line 37 -column 23, line 20	7,8
A	US 5 862 790 A (DAI WENGANG ET AL) 26 January 1999 (1999-01-26) abstract; figures 1,4-8 column 2, line 37 -column 3, line 6 column 3, line 60 -column 8, line 65	1,6-8,10
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<div style="display: flex; justify-content: space-between;"> <span><input checked="" type="checkbox"/> Further documents are listed in the continuation of box C.</span> <span><input checked="" type="checkbox"/> Patent family members are listed in annex.</span> </div>		
<div style="display: flex;"> <div style="flex: 1;"> <p>* Special categories of cited documents:</p> <p>*A* document defining the general state of the art which is not considered to be of particular relevance</p> <p>*E* earlier document but published on or after the international filing date</p> <p>*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>*O* document referring to an oral disclosure, use, exhibition or other means</p> <p>*P* document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="flex: 1;"> <p>*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>*X* document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>*Y* document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>*G* document member of the same patent family</p> </div> </div>		
Date of the actual completion of the international search  <b>27 March 2001</b>		Date of mailing of the international search report  <b>03/04/2001</b>
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016		Authorized officer  <b>Döring, M</b>

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/GB 00/04974

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>DE 198 18 596 A (DAIMLER CHRYSLER AG)  25 November 1999 (1999-11-25)  abstract; claims 1-4,6-9; figures 1-3  column 1, line 3 - line 39  column 2, line 56 -column 3, line 18  column 3, line 50 -column 6, line 19  -----</p>	<p>1-3,6-8,  10</p>

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Information on patent family members

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